An Agent-Based Simulation for Water Sharing Between Different Users

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Paper prepared for presentation at the X[th] EAAE Congress
'Exploring Diversity in the European Agri-Food System',
Zaragoza (Spain), 28-31 August 2002

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Abstract. Water sharing has become a serious problem in France. One of the objectives of 1992 and 2000 directives proposed by the European Union was to reduce both the frequency and the extent of water conflicts through the establishment of multilateral negotiations, where different public and private interests can be represented in a structured institutional environment. In France, many negotiations take place at local level between farmers, water suppliers, public services and environmentalists to allocate water resources between users. We suggest that Agent–Based Modelling (ABM) using a multi-agent approach could help negotiations between different players by showing the consequences of water allocation rules and taking in consideration the players' respective attitudes and their ability to change their behaviour.
Keywords. Multiagent-based simulation, user and agent modelling, conflict resolution and negotiation, irrigation application.

1. INTRODUCTION

The water directive introduced by the European Union in 2000 reinforces the institutional and legal aspects of the 1992 water directive to encourage public participation in water distribution for big hydrographical areas. One of the objectives of these different laws is to reduce the frequency and extent of water conflicts through the establishment of multilateral negotiations, where different public and private interests can be represented in a structured institutional environment.

The aim of these negotiations is to reach a compromise that will improve the situation of some people of the parties with the agreement of the others. But few are in position to negotiate, notably because of the lack of tools and methods necessary to collectively assess the impact of the different scenarios and to organise the negotiation. In France, farmers irrigate land more and more in order to increase income and security and water sharing has become a serious problem. At a global level, the public authorities define principles governing water management. At a local level, regulations result from negotiations between farmers, water suppliers, public services and environmentalists. The results obtained are very complex, are more often not a reflection of the power struggle between the different parties and no attention is paid to the consequences of the different regulations. When the rule is very complex, it is difficult to say what the future revenue and water consumption of the farmers will be. In some cases tools from economic theory have been used. To define prices, quotas and regulations different approaches have already been used. Models based on linear programming and/or game theory have shown the interest of such approaches. The first part of this paper presents the models which have been used in irrigation. It goes on with a rapid review of decision theory before introducing in the second part the Agent-Based Modelling (ABM) system under construction and its initial results.

2. EXISTING MODELS

2.1. Linear programming approaches

Concerning irrigation, several applications have been developed in France concerning groundwater use in the Beauce region [12] or e water use of the Charente River [20], for example. In both models, the authors maximised a global utility function and used shadow prices to determine quotas or water prices. But taking

irrigation issues into account raises specific limitations:
- Most coefficients of the economic function represent a crop margin, which depends on yields and prices. These coefficients are random and often the authors maximise the expected margin. Some applications try to maximise an expected income with a limited level of risk.
- Water availability and crop water needs are random variables.
- Not all decisions are taken at the same time; some are related to complementary information. For example a farmer decides to sow without knowing what the climate will be and he will irrigate according to the rainfall.

2.2. Game theory approaches

The aim of game theory [16][18] is to formalise the agent decision-making process in a context where each agent tries to optimise its own utility function with respect to the other agents. One of its main outcomes is the emergence of equilibrium states, i.e. situations where no agent has an interest to diverge. Game theory models provide some valid models at economic level and in different social situations with few players [13].

An application was implemented in the Adour Basin where, in order to estimate farmers' income, the authors [27] used a linear program to determine income according to water price and allocated amounts of water. In the case of the Farmer agent, this linear function was transformed into a concave decreasing function (increasing the allocated water amount function and decreasing the water price function). On the contrary, the utility function of the Environmentalist agent is related to river flow. For the Taxpayer agent the utility function is a decreasing function of hydraulic investment.

This type of model is built with a very strong hypothesis:

- Quantification of political weight for each player.
- Determination of (concave and continuous) utility function for each player.
- Instability of the solutions, which require numerous repetitions to get stable results.

2.3. Comments based on these two approaches

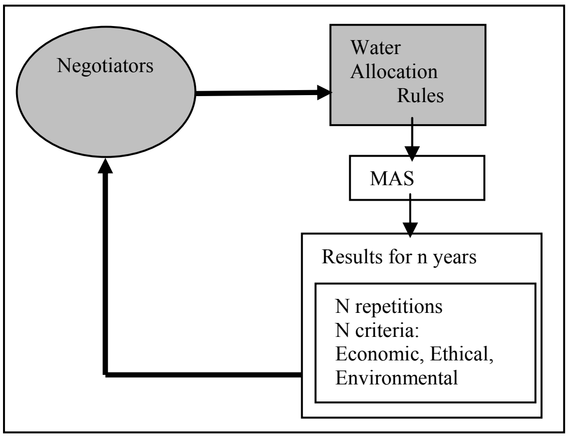
- These models are somewhat limited because they only take into account a few decision-makers [13] and are often monoperiodic.
- They assume perfect knowledge of possible solutions and their consequences.
- These different approaches don't take time into account and take only one collective criterion as a basis.
- These models do not take the evolution of production systems into account, nor do they consider the different player learning processes.
- Both assume that the decision-maker is acting completely rationally.
- In the second approach, the representation of agents as constrained maximising algorithms restricts the density of the network of agent interactions as underlined by Moss [13] in a recent publication where he describes current practice in game theory literature.

2.4. Agent-Based Modelling

In opposition to the above mentioned approaches we think that Agent-Based Modelling, where simulations are based on multi-agent systems, provides new solutions [8][13][15] that is to say:
- Takes into account many agents with different behaviours.
- Enables agents to learn and to change their behaviour in the light of new information.
- Simulates agent evolution over a long period in term of growth and bankruptcy.
- Considers alliances and lobbies linked to exchanges between agents.

We do not intend to provide the optimal solution but only to show real negotiators the possible consequences of the water allocation rules they have decided, according to different criteria: economic (global output), ethical (disparities between agents), environmental (water savings). (Figure 1)

Figure 1. Model role in the negotiation



3. OBJECTIVES

The objective is to show over a number of years the evolution of a group of farmers who use a limited water resource. This resource is managed by a water supplier who allocates water to each farmer in accordance to the regulations. The amount of water consumed depends on the climate of the year, the irrigated area and the level of irrigation. The crop yields are related to rainfall and water allocation. We considered that the actors of the water allocation process are the following:

- The farmers: each of them has cash money, order on crop preferences, objectives and an attitude towards risk. He has a crop area divided into plots and his own irrigation capacity. Each year he decides his cropping plan, which must respect his crop preferences and agronomic rules. This order is partially related to crop yield, which depends on the climate of the year (unknown when he takes his decision) and on the water available. Possibly at this time he could negotiate with the water supplier for the water he needs. At the end of the year, after his economic results, each farmer can modify his crop preferences and decide whether or not to invest in more irrigation capacities.
- The water supplier: each year he has an amount of water that he allocates to the different farmers. He has expenses and must balance his accounts.
- The information supplier: each year he receives the individual farmers' economic results, analyses and classifies them and sends a global report to each farmer.

4. MODEL DESCRIPTION

After this short description of the actors(1), we will transform them into agents. By agents we mean entities that are autonomous loci of decision-making: they decide and act [8][15]. A Multi-Agent System is composed of a set of computer procedures [10][15][28] where several agents share the same resource, limited or not, and communicate with each other. The current model is a generic one and does not correspond to a local situation. We have tried to Keep It as Simple as Suitable (KISS) using Axelrod's principle [1] as reformulated by Conte [5].

Our modelling approach takes into account two types of agents (Table 1):

- Cognitive agents: generally speaking they follow a Perception-Decision- Action cycle [2][22][28][30].
- Reactive agents: they are represented much more simply than the cognitive agents are but they are also more numerous and active [9]. These agents have inherited artificial life. They follow a Perception-Action cycle [10][29][30].

In the model, the cognitive agents (farmers, water supplier) are composed of knowledge, strategies, information memory and communication modules. They have to take decisions, so they must be rational [17] and the model builder has to choose which type of rationality. Roughly speaking there are three possible types of rationality as defined by Decision-Making Theory [21]: substantial [19] [29], bounded [25] and adaptive [6].

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(1) [3] " It is right to distinguish between a data processing agent and an economic agent although one can build data processing agents representing some economic agents. " Hereafter we will use the term agents for computer entities and actors for the real world.

Table 1. Agents in the model developed.

Agents	Number	Type
Farmers	n	Cognitive
Water Supplier	1	Cognitive
Information Supplier	1	Reactive
Crops	n	Reactive
Climate	1	Reactive

Some authors suggest that agents have substantial rationality, so they try to reach an optimum and they are endowed with optimisation skills. We think it would be more realistic, following the criticisms levelled by Simon [26] and Cyert and March [6], to endow our agents with a bounded and adaptive rationality.

The structure of reactive agents (crops, climate) is only made up of knowledge and communication modules.

Let us now examine the main components of a cognitive agent (farmer agent) and a reactive agent (climate agent).

4.1. A cognitive agent model

This type of agents is composed of four modules: a knowledge module, a strategy module, a communication module and a memory module. In our system, farmer agents are represented as cognitive agents.

1. The knowledge module is divided into three parts:

- A database containing data including farm area, crops classified in order of preference based upon profitability and water consumption.
- A database containing calculation procedures for water requirements, crop yields related to rainfall and water allocation, for example.
- A database containing decision-making procedures made up of a set of production rules to determine cropping plan, irrigated crops, water amount, among others.

2. The strategy module, corresponding to a set of rules to enable each farmer agent to reach its own goal.

Since these agents have different objectives, such as increasing or not their revenue and their security level, the strategy module contains rules which can evolve over time with respect to new information and better knowledge of other agent behaviours. The agents decide how to negotiate, what crop yield objective should be reached according to climate conditions, and the minimum cash level to be invested.

3. Two communication modules in accordance with the type of information exchanged: the private information module and public information module.

- Private information is processed via a mailbox and messages. Each agent can send a message to the mailbox of a receiver, which has the means to process it. In the same way, it can receive a message in its personal mailbox and process it. This technique is used by farmer agents in their relation to the water supplier agent and information supplier agent.
- Public information exchange is a technique where an agent sends public or semi-public information. This information can be processed by agents which have the method to retrieve it. For instance, the climate agent sends public information about the climate of the year which is used by the farmer agent to calculate crop yields.

4. A memory module, which is a record of information exchanged with other agents.

4.2. A reactive agent model

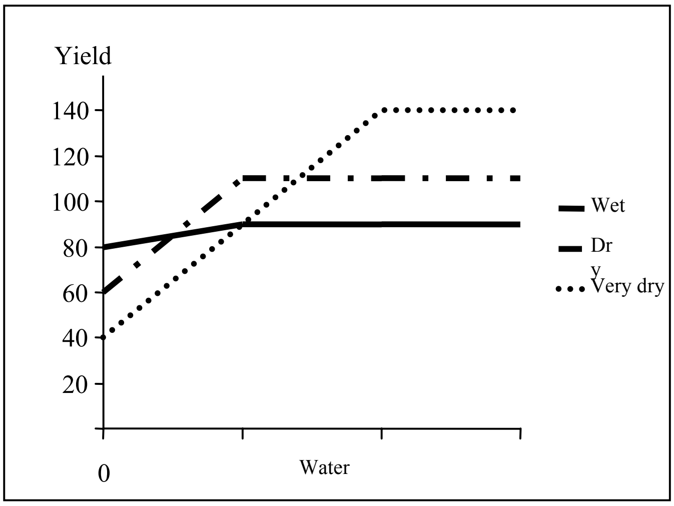
This type of agents is composed of two modules: a knowledge module and a communication module. In our system, the climate agent is represented as a reactive agent.

1. The knowledge module is divided into two parts:

- A database, containing individual information on each agent.
- A database containing calculation procedures.

For instance the climate contains the probability of different types of weather (Wet, Dry, Very Dry) and a function to select randomly the type of weather for a given year. The type of weather allows the crop agent to select which water answer curve to use (figure 2). The crop agent communicates its choice publicly to the farmer agents, which calculates its yield in function of the water used.

Figure 2: water answer curve



2. Communication module where there is a method to send public information

5. MODEL IMPLEMENTATION

The general structure is composed of classes, attributes and methods as presented in the UML diagram (figure 3).

This is a discrete event simulator [11], which is a sequential process of unrelated events. The simulation is carried out over a number of years (12), each of which is made up of four sequences.

5.1. Determination of the cropping plan

Each farmer agent determines its cropping plan and its water needs. This is an iterative procedure: a farmer agent determines a first cropping plan, fixes its yield objectives for a climatic type of year according to its behaviour and calculates its global water needs. This request is made at a time when neither the climate of the year nor the other water requests are known.
The water supplier agent receives a set of water requests, adds them up and proposes an amount of water to each farmer agent in accordance with the water allocation rule being tested.

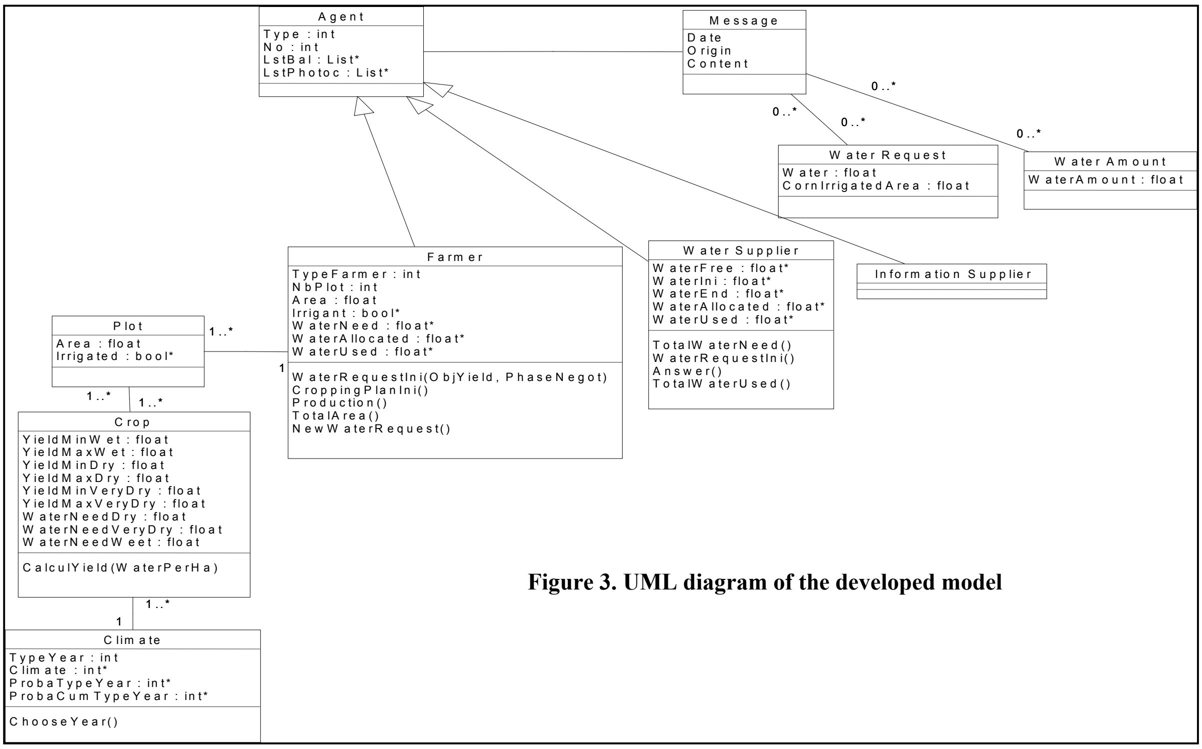


Figure 3. UML diagram of the developed model

Each farmer agent receives information about the amount allocated to it.
These exchanges stop when the water supplier agent has no more water to allocate or no new requests. The water supplier agent determines its answer in accordance with the regulation tested.

For the exchange between farmer agents and water supplier agent we have defined a protocol inspired by the MALE protocol described by Sian [24] (figure 4).

5.2. Climate determination and crop growth

The climate of the year is determined at random. In accordance to the type of climate each crop agent has a method to select the water answer curve to use to calculate yields.

5.3. Economic results

Each farmer agent calculates its yields and its economic results. It sends its results to the information supplier, which synthesises the information coming in from each farmer agent.
The information supplier agent provides each farmer agent with global information concerning the highest, average and lowest revenues and crop yields.

5.4. Decision-making

Each farmer agent decides whether or not to invest in more irrigation capacities and possibly to change its behaviour.

6. INITIALS TESTS AND PRELIMINARY RESULTS

The model has been written in C++ under Builder5, the model interfaces are shown in the figure 7. We chose this tool because of the ease with which object classes can be defined, quality of the interfaces and the low runtime. The initial simulations have been done with the following elements:

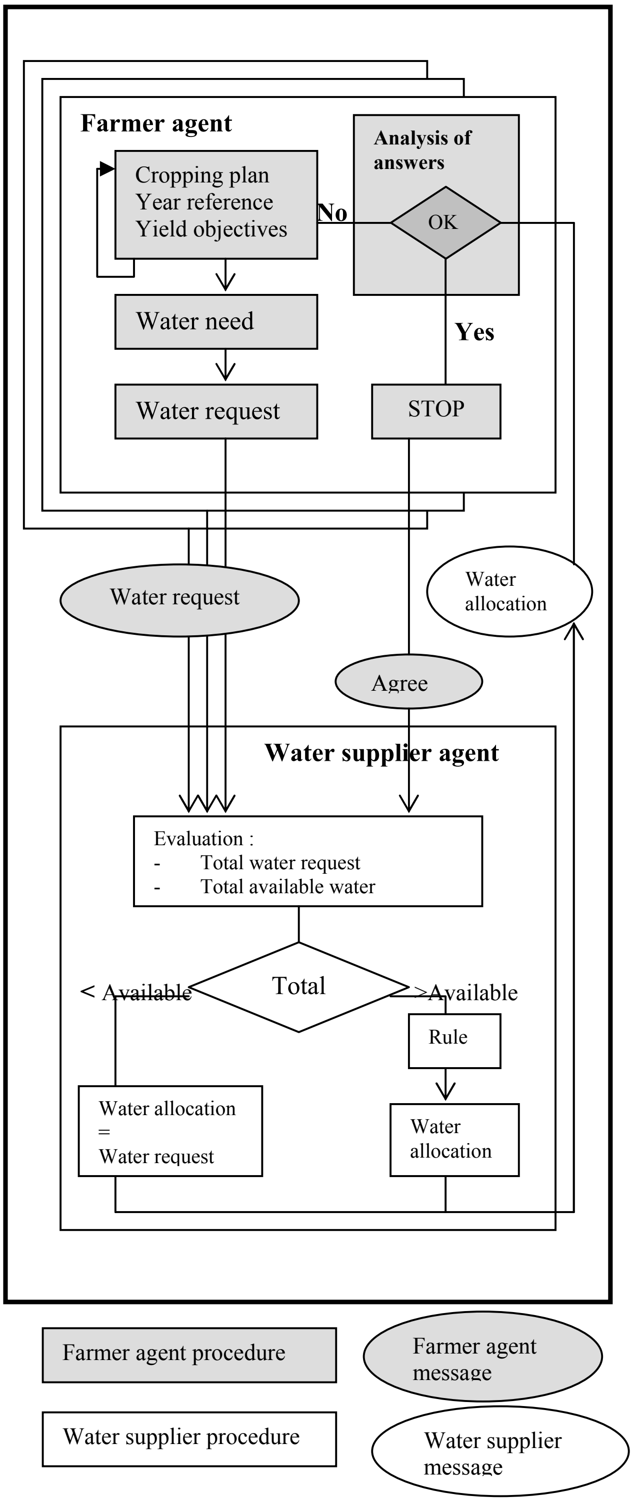
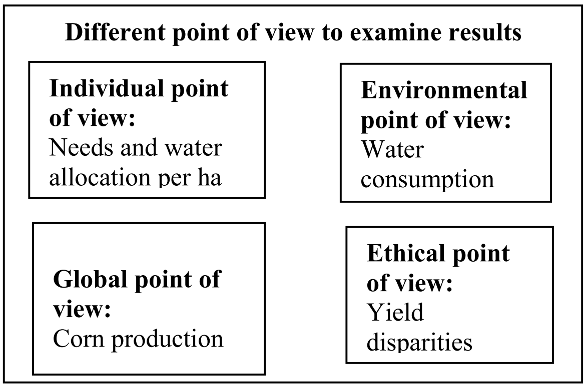


Figure 4. Exchange protocol between agents

- Three types of climatic years: Wet, Dry and Very Dry.
- One hundred farmer agents with the same crops but with different areas.
- Water availability fixed at a level that is slightly above dry year needs.
- Water allocation rules.

The model evolves progressively by following the analysis of results for each water allocation rule tested. The results can be examined from different points of view as shown in figure 5.

Figure 5: How to analyse model results



In our model different types of rules are tested. Three of them are explained below:

- **R1: Rule based on water requests pro rata:**

"If the amount of water requested is less than the water available, Then each farmer agent can use the amount of water requested.
Else water is allocated in function of the request pro rata."

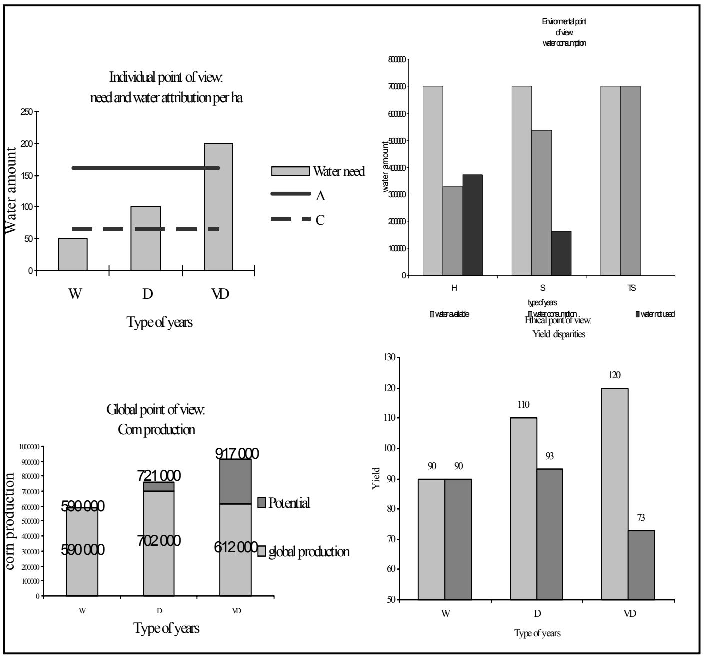
Two farmer agent behaviours have been considered:

The first one (A) is greedy and selfish: the farmer agent asks for 120% of its water needs in very dry years.

- The other one (B) is reasonable: it only asks for its water needs in dry years.

Figure 6 shows results using this rule. We can see that in the absence of reasonable farmer agents, global production is higher but heterogeneity of demands leads to great yield disparities. These results are paradoxical but can be explained as follows in: Increase heterogeneity of needs leads not only to a greater yield disparities but also to a global reduction in yield. This rule seems unsatisfactory both from the collective point of view and the ethical point of view.

Figure 6: Results of simulation: rule based on water demands pro rata without negotiation for 50 % A + 50 % B



- **R2: Rule based on crop areas irrigated:**

With this rule we obtained better results in the short run in terms of global production and disparities. The results are similar to those obtained with a rule based on a centralised economy.

- **R3: Rule based on requests with better knowledge of the others**:

The farmer agent has an adaptive rule; it knows the water allocation of each farmer and asks for the maximum amount of water allocated. Results show that we get the same results as before after three years in this bottom-up evolution, based on better knowledge, as in the top-down way of fixing water allocation (rule R1). Other simulations have been done, for example to test the possibility of decreasing disparities between small and big farmers through water allocation.

These initial results have been discussed with professionals in order to validate the model: do they understand the model, do they understand the results from the model. After these first results, the model is under modification to now being modified in order to introduce long-term effect on crop area evolution, water use and of farmers "disappearance" for economic reasons.

7. VALIDATION

Before improving this model we have to consider its validity or at least the methods needed to validate this type of model. The question of validation in a multi-agent approach is a real problem. Validation is not a procedure to test a scientific theory or to certify the truth of a scientist way of thinking but a means to decide if a model is acceptable with respect to its potential use. Validation is a demonstration of what a model (in its application domain) actually provides on a scale of satisfaction compared to the results we expected from the model. But how should we decide if a model is acceptable for its future use? How can we decide if a system is good or not in the light of its results?

Researchers are not agree on validation methods. Following Rykiel [24] and Moss [14] two types of validation can be considered:

- Operational validation: this is a protocol (statistical tests) that shows if the model output correspond to the model objectives. This is a comparison between simulated data and observation in the real world. If the context changes the model must be revaluate.
- Conceptual validation which tests whether assumptions in the model are correct.

There are moreover types of validation procedures proposed by different group of researcher [7] [17] [24]:

- Face validity: it is a surface or initial impression of the realism of a model by a group of experts that know the domain.
- Output comparison with other validated models.
- Output statistical validity (T Test; KS test, Turing test).
- Predictive power: testing and comparing the results of the model against reality.
- Ease of the utilisation of the model.
- Flexibility of the model or how a model evolve with modifications.
- Internal validation using a set of data we could test if the output are consistent step by step at a runtime.
- Data validation.

Taking into account the proposals made by different group of researcher [7] [17] [24] we have been led to consider the following elements:

- Data validation (input data, methods).
- The ability of the model to answer questions (predictive power) that we formulate as follows:
  a. Users' understanding of the model (face validity).
  b. Users' understanding of the results of the model (called result confirmation).
- The ability for users to use the model (ease of use).

To satisfy the above requirements, we have designed the following experiments:

- We first built a very simple generic model using general agronomic data that agronomists agreed about production functions. We proposed this simple generic model to decision-makers. They understood quickly the principles of the model if we didn't insist on details of multi-agent modelling.
- Then we presented the preliminary results to decision-makers. They accepted immediately. They were even considered to be merely stating the obvious and of no interest: of course, a rule based on water needs pro rata is going to give more water to farmers who ask for more. It is only after showing the different consequences (in terms of yield disparities and global production) of different behaviours that we see an increased interest on the part of the decision-makers; they imagine new water allocation rules and ask to see the consequences.
- Finally, we got the following conclusion: we can get the same satisfactory results in terms of

both collective interest and a reduction in disparities either in an authoritative way or in a decentralised way by providing more information to farmer agents. This conclusion corroborates the results of the economic theory.

8. CONCLUSIONS

This paper shows an already operational system of Agent-Based Modelling which could be an element in the negotiation for water sharing. At this stage, the model developed is not a negotiation model. It intends only to present to the actors involved in the negotiation process the consequences of water allocation rules. The experience gained from the development effort of our model supports the proposition that agent-based simulation is an appropriate modelling framework to test water allocation rules. First, Agent–Based Modelling is well adapted to modelling many types of agents with different rationalities. Second, environmental problems, which are very complex, may be modelled satisfactorily by distributed artificial intelligence. Third, multi-agent systems provide an adequate structure to represent multiple and complex interactions between cognitive agents (farmers and water supplier agents), which are composed by complex knowledge modules, and reactive agents (crops and climate agents) that have an important place in the global structure for water allocation.

More research has to be done in several directions: (1) improvement and extension to other types of water resource (river and water table); (2) real world experiments to tell us if we should to keep it as a model to help negotiations or if we should develop it as a negotiation model, (3) improvement of the model by adding communication between farmer agents (conflict resolutions, grouping of farmer agents); (4) improvement of the water allocated model by introducing a variable time; (5) improvement of the model by integrated approaches of the multi-agent community game theory.

A question needs to be settled: is it necessary to stay at a generic model level or should we create a model representing a complex reality? In this case many field studies must be carried out and the problem of the typology of the players, their behaviours and their different relation networks and influence must not be forgotten. On the contrary, a generic model, which doesn't aim to draw fine distinctions, would allow us to take into account a great diversity of agents with different attitudes, based on game theory. A recent publication [4] shows us that extremely simple models devised by physicists would shed a new light on the old wealth-sharing problem as posed by Pareto a century ago.

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Figure 7 : Model interfaces